# Computational Fluid Dynamics
# Past, Present and Future

**Prof. Antony Jameson**
Department of Aeronautics & Astronautics
– *Aerospace Computing Laboratory* –
Stanford University
jameson@baboon.stanford.edu

SciTech 2015
January 7, 2015

# Outline

I. **The History of CFD**
- Van Leer's View
- Emergence of CFD
- Multi-disciplinary Nature of CFD
- Hierarchy of Governing Equations
- 50 Years of CFD
- Advances in Computer Power

II. **Author's Experience**
- CFD Code Development
- FLO and SYN Codes
- Wing Optimization Using SYN107

III. **Usage of CFD**
- Boeing's Experience
- Airbus's Experience

IV. **Current & Future Trends**
- The Current Status of CFD
- The Future of CFD (?)
- Large-Eddy Simulation

V. **Overview of Numerical Methods**
- Typical Requirements of CFD
- A Review of the Literature
- DG and related Discontinuous Finite Element methods

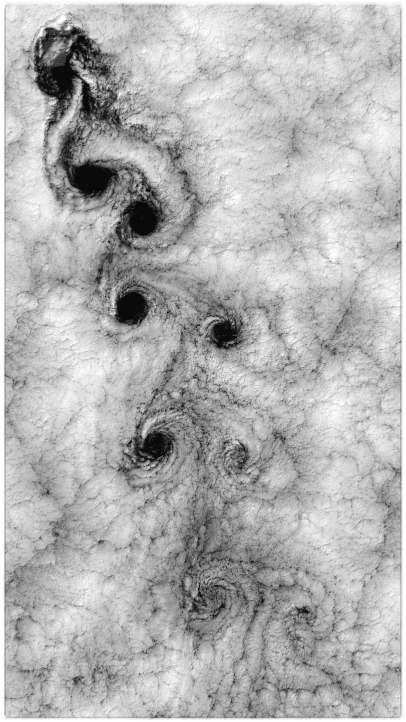
VI. **Research on the FR Methodology**
- ESFR
- OFR
- Shock detection
- Non-linear stabilization via Filtering

VII. **Applications**
- Transitional Flow over SD7003 Airfoil
- Study of Flapping Wing Sections
- Flapping Wing Aerodynamics
- Flow Over Spheres

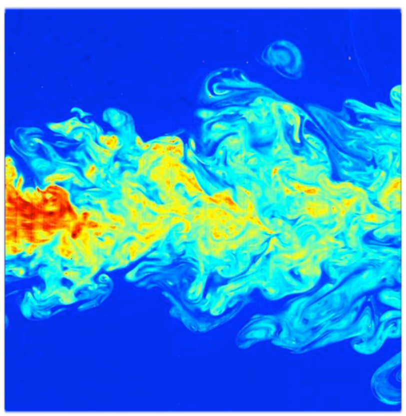
VIII. **LES Computations**
- Taylor-Green Vortex
- Flow past a Square Cylinder

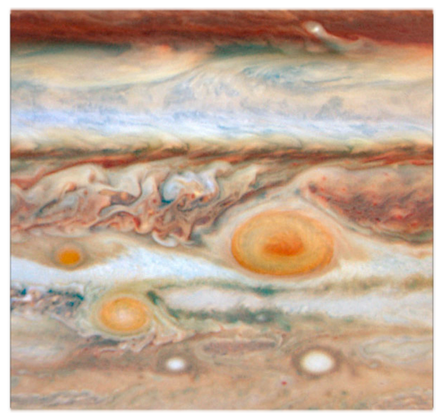
IX. **Summary and Conclusions**

# Context



*"When I die and go to Heaven there are two matters on which I hope enlightenment. One is quantum electrodynamics and the other is turbulence. About the former, I am really rather optimistic."*





**<u>Sources:</u> Wikipedia.org; NASA.gov; Hubblesite.org; *et al.*; H. Lamb (1932)**

# Outline

I. The History of CFD
- Van Leer's View
- Emergence of CFD
- Multi-disciplinary Nature of CFD
- Hierarchy of Governing Equations
- 50 Years of CFD
- Advances in Computer Power

II. Author's Experience

III. Usage of CFD

IV. Current & Future Trends

V. Overview of Numerical Methods

VI. Research on the FR Methodology

VII. Applications

VIII. LES Computations

IX. Summary and Conclusions

# History of CFD in Van Leer's View

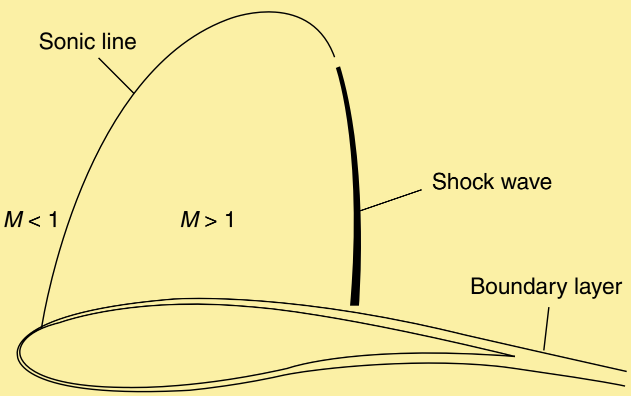
# Emergence of CFD

- In 1960 the underlying principles of fluid dynamics and the formulation of the governing equations (potential flow, Euler, RANS) were well established
- The new element was the emergence of powerful enough computers to make numerical solution possible – to carry this out required new algorithms
- The emergence of CFD in the 1965–2005 period depended on a combination of advances in computer power and algorithms.

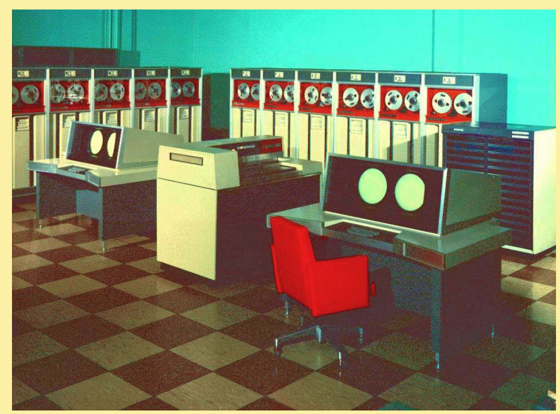
**Some significant developments in the '60s:**

- birth of commercial jet transport – B707 & DC-8
- intense interest in transonic drag rise phenomena
- lack of analytical treatment of transonic aerodynamics
- birth of supercomputers – CDC6600

**DC-8**

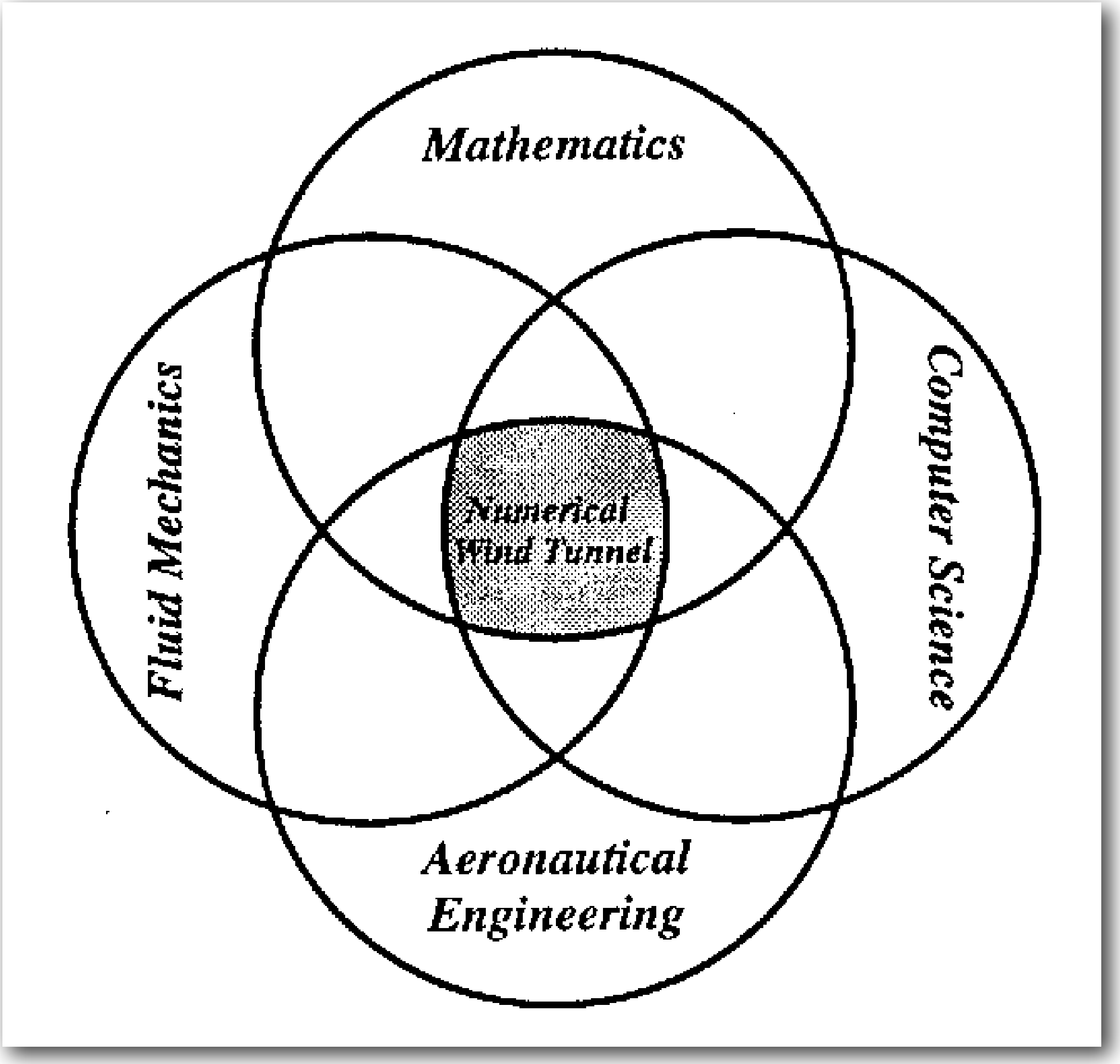



**Transonic Flow**

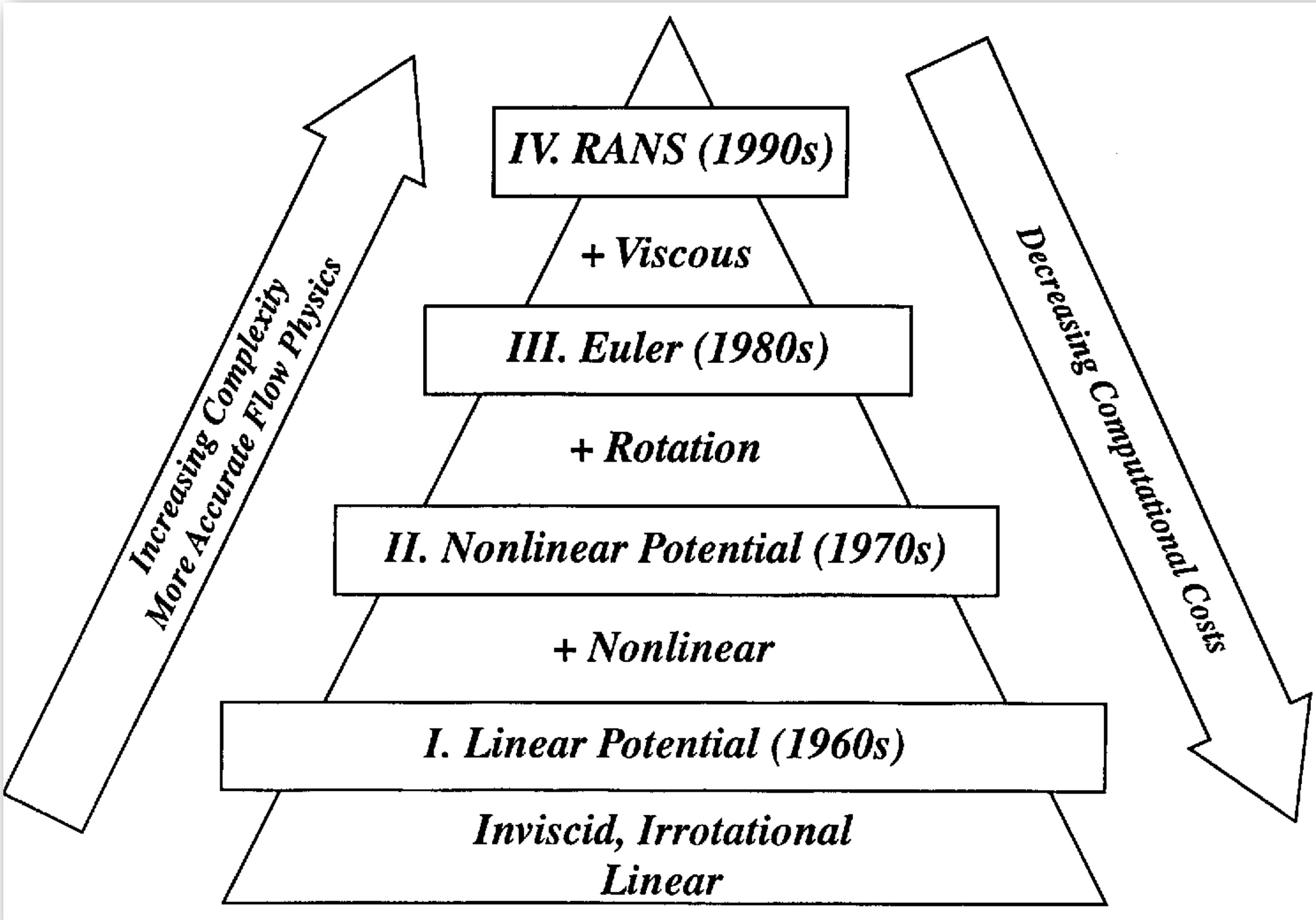


**CDC6600**

# Multi-Disciplinary Nature of CFD



# Hierarchy of Governing Equations



# 50 Years of CFD

- 1960–1970: **Early Developments**

  Riemann-based schemes for gas dynamics (Godunov), 2nd-order dissipative schemes for hyperbolic equations (Lax-Wendroff), efficient explicit methods for Navier-Stokes (MacCormack), panel method (Hess-Smith)

- 1970–1980: **Potential Flow Equations**

  type-dependent differencing (Murman-Cole), complex characteristics (Garabedian), rotated difference (Jameson), multigrids (Brandt), complete airplane solution (Glowinsky)

- 1980–1990: **Euler and Navier-Stokes Equations**

  oscillation control via limiters (Boris-Book), high-order Godunov scheme (van Leer), flux splitting (Steger-Warming), shock capturing via controlled diffusion (Jameson-Schmit-Turkel), approximate Riemann solver (Roe), total variation diminishing (Harten), multigrids (Jameson, Ni), solution of complete airplane (Jameson-Baker-Weatherill)

- 1990–2000: **Aerodynamic Shape Optimization**

  adjoint based control theory

- 2000–2010: **Discontinuous Finite Element Methods**

  Discontinuous Galerkin, Spectral Difference, Flux Reconstruction, *etc.*

# Advances in Computer Power

| | | | |
|---|---|---|---|
| **1970** | CDC6600 | 1 Megaflops | **$10^6$** |
| **1980** | Cray 1<br>Vector Computer | 100 Megaflops | **$10^8$** |
| **1994** | IBM SP2<br>Parallel Computer | 10 Gigaflops | **$10^{10}$** |
| **2007** | Linux Clusters | 100 Teraflops | **$10^{14}$** |
| **2007** | (affordable) Box Cluster in my house<br>Four 3 GHz dual core CPUs (24 Gigaflops peak)<br>$10,000 | 2.5 Gigaflops | **$2.5\times10^9$** |
| **2009** | HP Pavilion Quadcore Notebook<br>$1,099 | 1 Gigaflops | **$10^9$** |
| **2011** | MacBook Pro Quadcore Laptop<br>$2,099 | 2.5 Gigaflops | **$2.5\times10^9$** |

# Outline

# CFD Code Development

- 1970–1980: **Potential Flows**

  solution of inverse problem by conformal mapping (SYN1), solution of 2D potential flow by conformal mapping (FLO1), 2D transonic potential flow using rotated difference scheme (FLO6), first transonic potential flow solution for a swept wing (FLO22), 3D potential flow in general grid with trilinear isoparametric elements (FLO27), multigrid solution of 2D transonic potential flow (FLO36)

- 1980–1990: **Euler & Navier-Stokes Equations**

  solution of 3D Euler (FLO57), multigrid solution of 3D Euler (FLO67), multigrid solution of 2D Euler (FLO82), first solution of Euler equations for a complete aircraf with tetrahedral meshes (FLOPLANE), cell-vertex and cell-centered schemes for 3D Navier-Stokes (FLO107)

- 1990–2000: **Aerodynamic Shape Optimization**

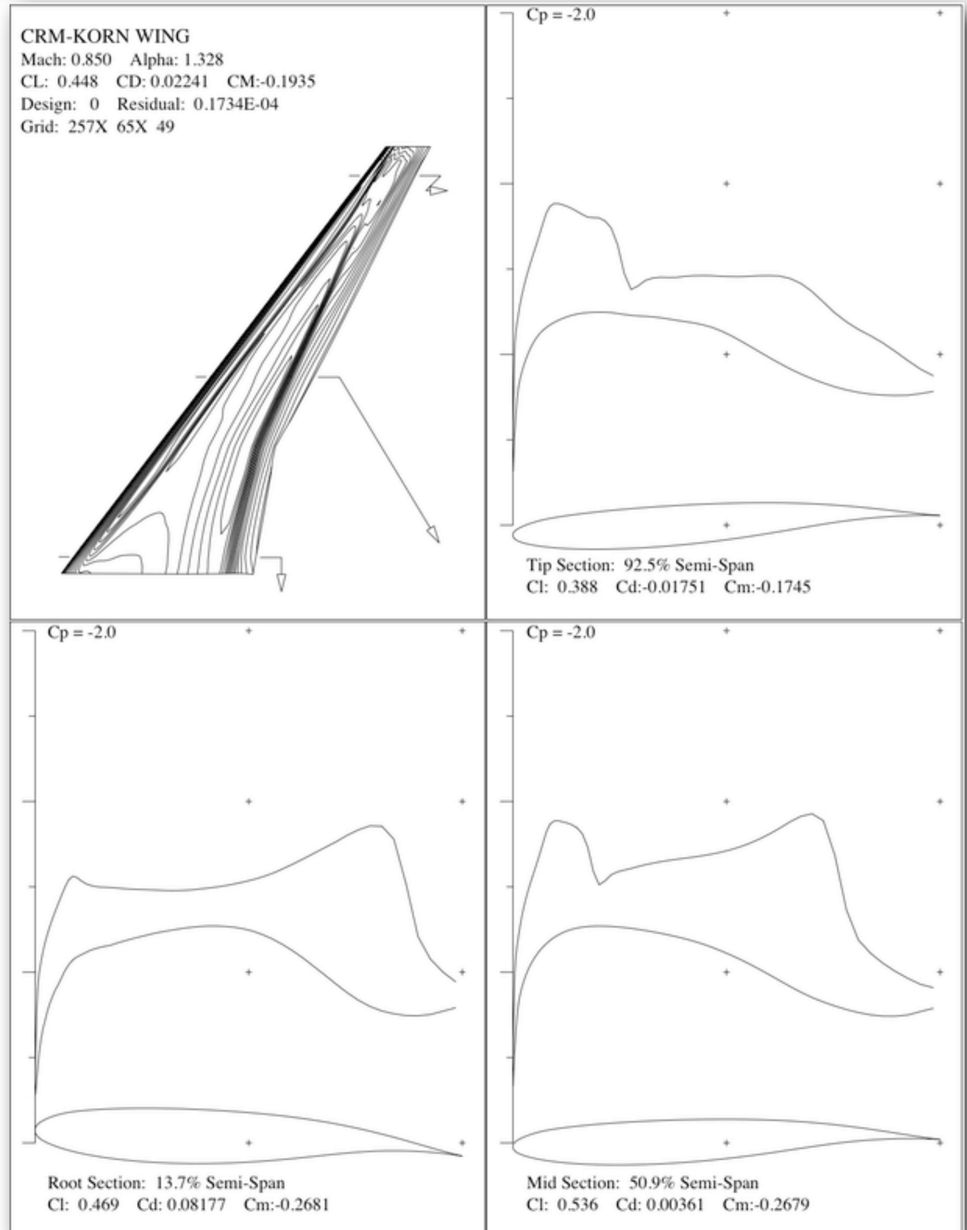
  airfoil design via control theory using 2D Euler (SYN83), wing design using 3D Euler (SYN88), airfoil design using 2D Navier-Stokes (SYN103), wing design using 3D Navier-Stokes (SYN107), aerodynamic design of complete aircraft with tetrahedral mesh (SYNPLANE), viscous flow solution on arbitrary polyhedral meshes (FLO3XX)

- 2000–2010: **High-order Methods for Navier-Stokes Equations**

  high-order discontinuous finite element methods for unsteady compressible Navier-Stokes equations on unstructured meshes (Spectral Difference Method, Energy Stable Flux Reconstruction Method)

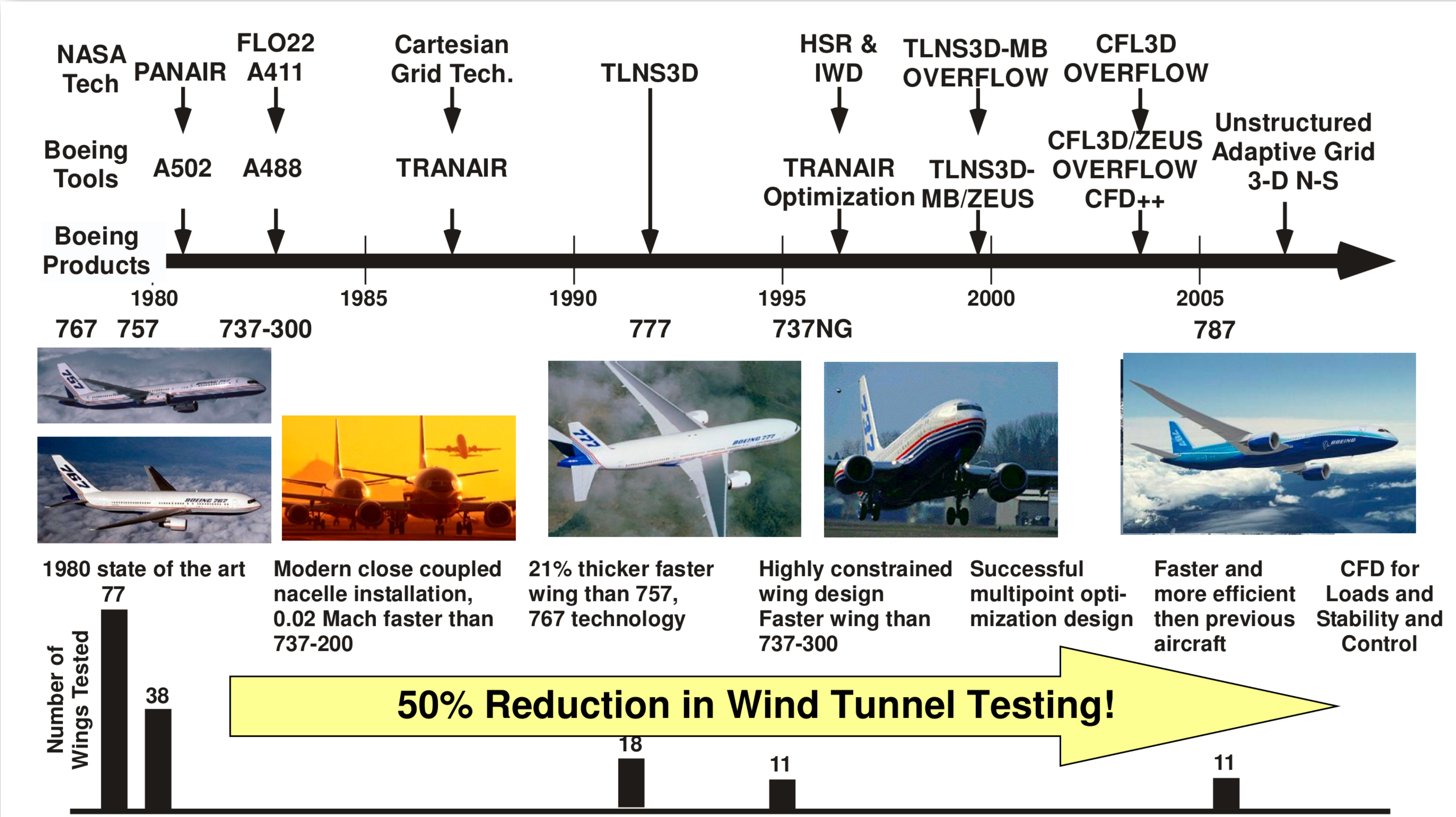
# Wing Optimization Using SYN107

**State of the Art Wing Design Process in 2 Stages, starting from Garabedian-Korn Airfoil and NASA Common Research Model**



# Outline

# Impact of CFD on Configuration Lines & Wind Tunnel Testing



# Impact of CFD on B737-300 Program

1975 1976 1977 1978 1979 1980 1981 1982 1983 1984

20 Years of wind tunnel based development indicated nacelles cannot be placed too close to the wing without excessive drag

Joint CFD/Wind Tunnel Studies unlock the secret of nacelle/wing interference drag

707/CFM56 Design & Flight Test validated CFD concepts

737-300 Program initially rejected due to high cost of increasing landing gear length

Go Ahead

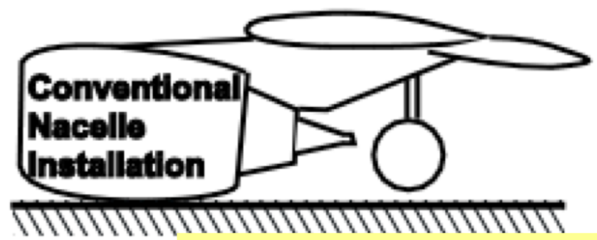
Roll Out

Certification

Initial Studies

737-300 Program

McDonnell-Douglas MD-80 Go Ahead




*Without the understanding gained from CFD there would not have been a 737-300 Program!*

**Walt Gillette**

Manager, 737 Aerodynamics - then

Vice President, 787 Engineering – retired

*5000+ Additional Sales!*

# Computational Methods at Boeing

**TRANAIR:**

- Full Potential with directly coupled Boundary Layer
- Cartesian solution adaptive grid
- Drela lag-dissipation turbulence model
- Multi-point design/optimization

**Navier-Stokes Codes:**

- CFL3D – Structured Multiblock Grid
- TLNS3D – Structured Multiblock Grid, Thin Layer
- OVERFLOW – Overset Grid

**N-S Turbulence Models:**

- S-A Spalart-Allmaras
- Menter's $k$-ω SST

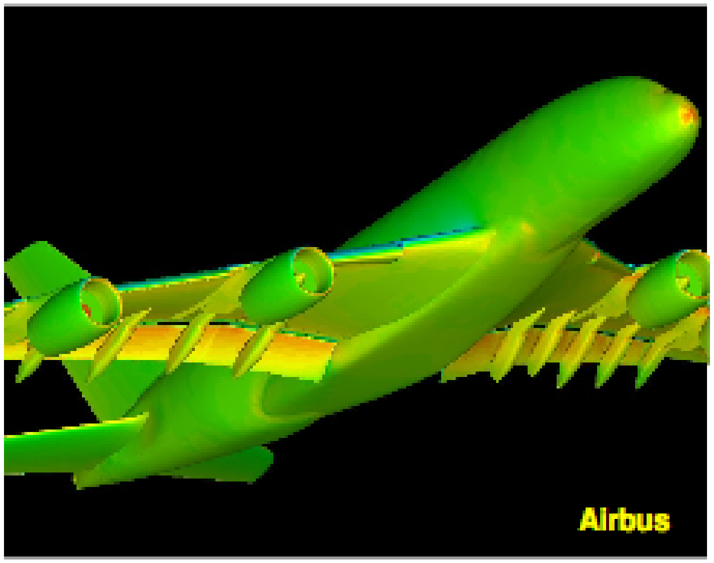
# CFD Contributions to B787

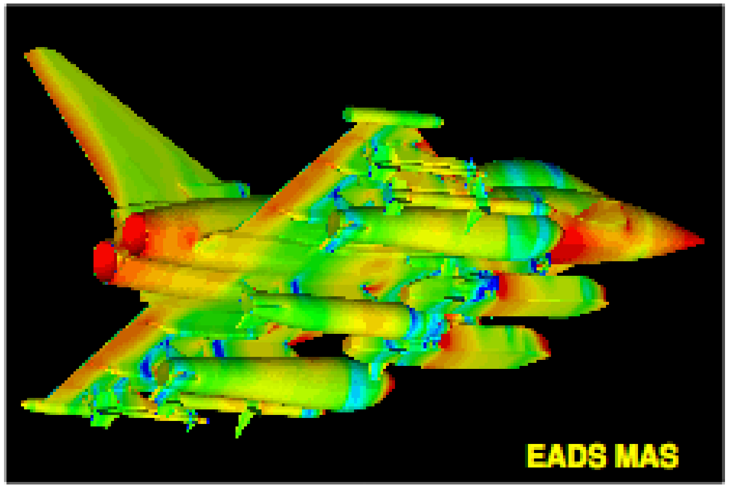
# CFD Development for Aircraft Design

## MEGAFLOW / MEGADESIGN
## - National CFD Initiative (since 1995)

**Development & validation of a national CFD software for complete aircraft applications which**

- allows computational aerodynamic analysis for 3D complex configurations at cruise, high-lift & off-design conditions
- builds the basis for shape optimization and multidisciplinary simulation
- establishes numerical flow simulation as a routinely used tool at DLR and in German aircraft industry
- serves as a development platform for universities

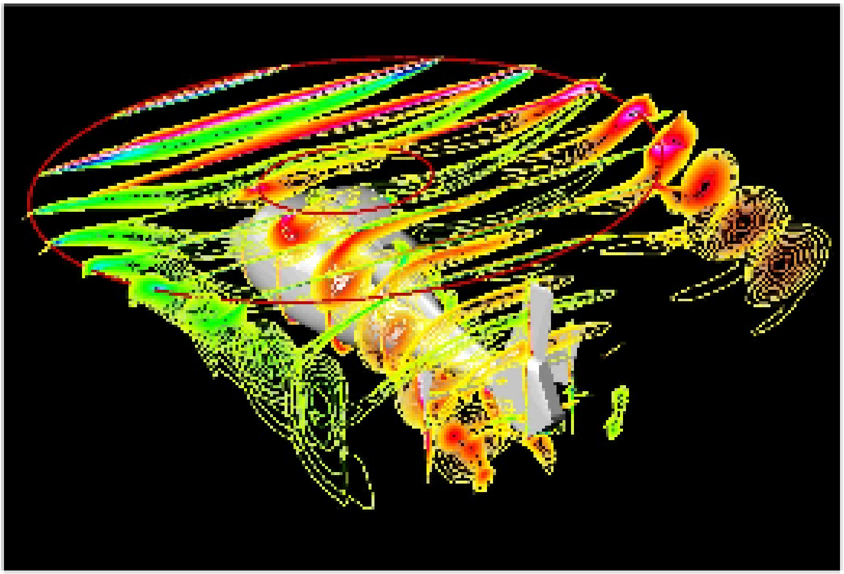


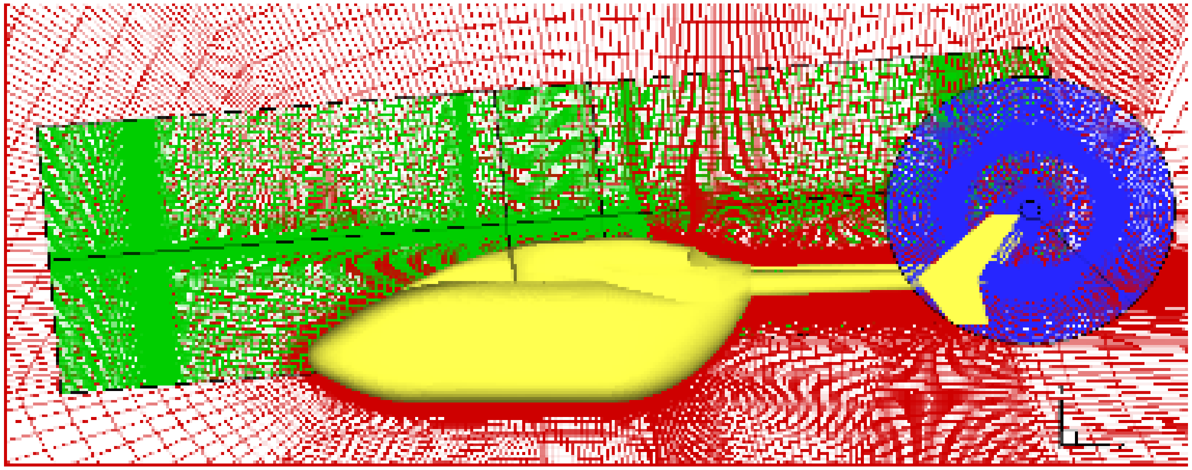



# Block-Structured RANS Capability: FLOWer

**Efficient simulation tool for configurations of moderate complexity**

- advanced turbulence and transition models (RSM, DES)
- state-of-the-art algorithms
  - baseline: JST scheme, multigrid
  - robust integration of RSM (DDADI)
- chimera technique for moving bodies
- fluid / structure coupling
- design option (inverse design, adjoint)





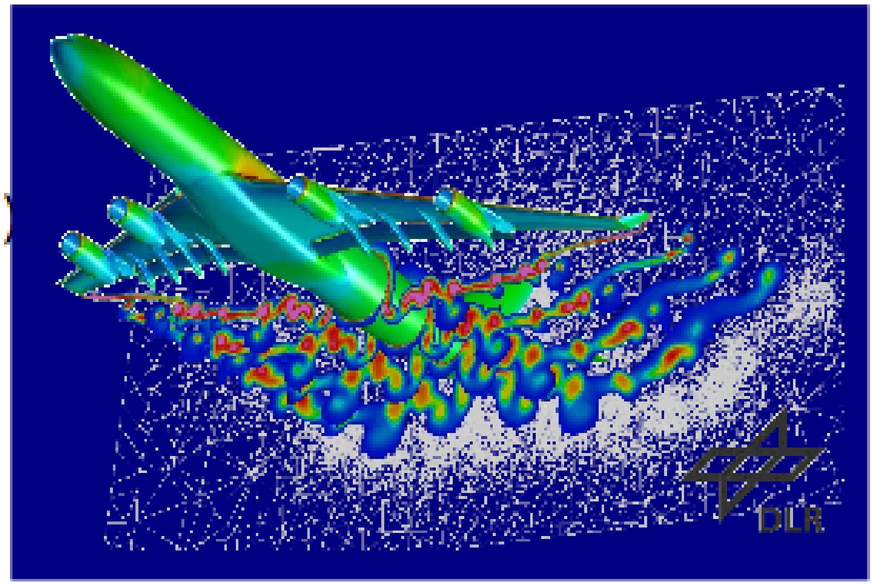
**FLOWer-Code**

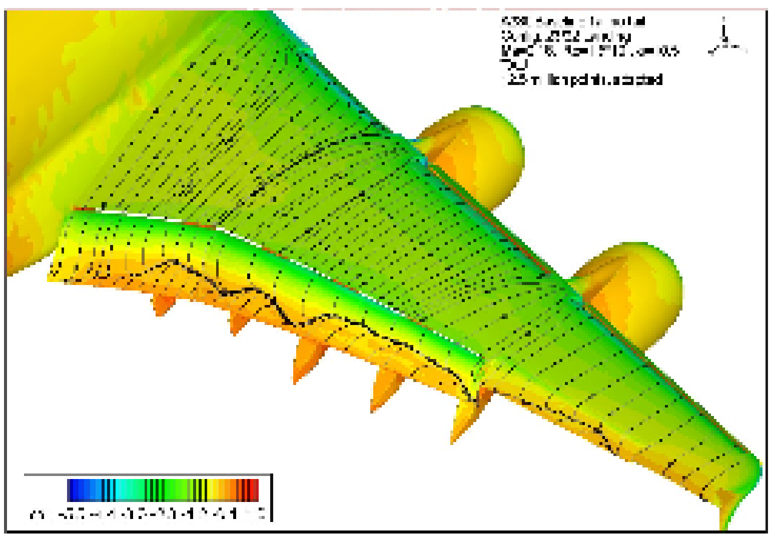
- Fortran
- portable code
- parallelization based on MPI

# Unstructured RANS Capability: TAU

## Tool for complex configurations

- hybrid meshes, cell vertex / cell centered
- high-level turbulence & transition models (RSM, DES, linear stability methods)
- state-of-the-art algorithms (JST, multigrid, ...)
- local mesh adaptation
- chimera technique
- fluid / structure coupling
- continuous/discrete adjoint
- extensions to hypersonic flows



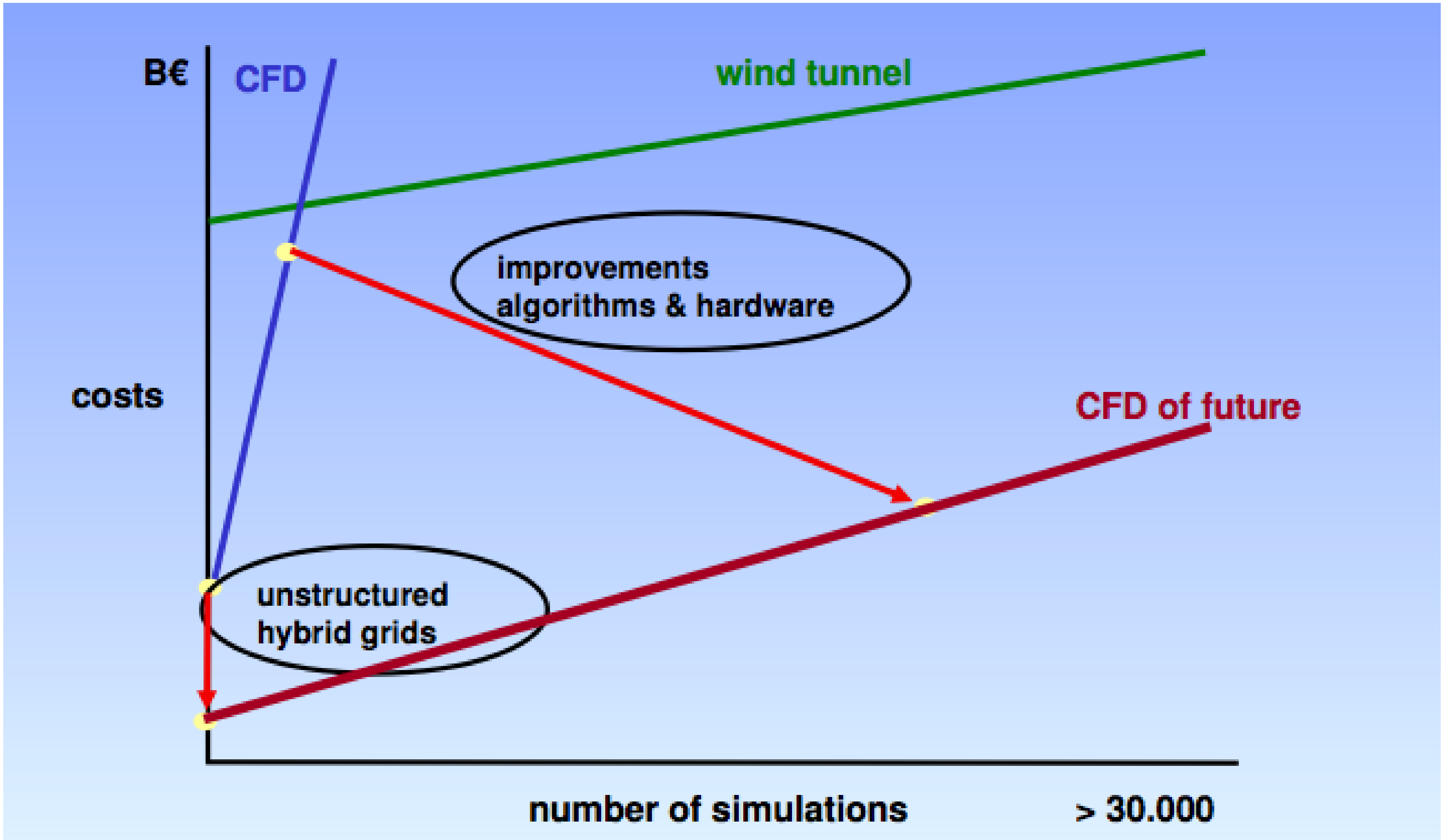



## TAU-Code

- unstructured database
- C-code, Python
- portable code, optimized for cache hardware
- high performance on parallel computer

# Numerical Flow Simulation

## Relation CFD / wind tunnel




✈ CFD cost effective alternative

# CFD Contribution to A380

# Outline

# The Current Status of CFD

- Worldwide commercial and government codes are based on algorithms developed in the ‘80s and ‘90s
- These codes can handle complex geometry but are generally limited to $2^{nd}$ order accuracy
- They cannot handle turbulence without modeling
- Unsteady simulations are very expensive, and questions over accuracy remain

# The Future of CFD (?)

**CFD has been on a plateau for the past 15 years**

- Representations of current state of the art:
  - Formula 1 cars
  - Complete aircrafts
- The majority of current CFD methods are not adequate for vortex dominated and transitional flows:
  - Rotorcraft
  - High-lift systems
  - Formation flying

# Large-Eddy Simulation

The number of DoF for an LES of turbulent flow over an airfoil scales as **$Re_c^{1.8}$ (resp. $Re_c^{0.4}$) if the inner layer is resolved (resp. modeled)**

**Rapid advances in computer hardware should make LES feasible within the foreseeable future for industrial problems at high Reynolds numbers. To realize this goal requires**

- high-order algorithms for unstructured meshes (complex geometries)
- Sub-Grid Scale models applicable to wall bounded flows
- massively parallel implementation

**Chapman (1979), AIAA J. 17(12)**

# Outline

# Typical Requirements of CFD

**Traditional numerical schemes for engineering problems are too dissipative and do not provide sufficient accuracy for LES and DNS**

| | |
|---|---|
| • **Accuracy:** | solution must be right |
| • **Small numerical dissipation:** | unsteady flow features |
| • **Unstructured grids:** | complex geometries |
| • **Numerical flux:** | wave propagation problems |
| • **High resolution capabilities:** | transitional and turbulent flows |
| • **Efficiency:** | code parallelism |
| • ... | |

# A Review of the Literature

**Past Research on DG Schemes:**

- Modern development of DG schemes for hyperbolic conservation laws stems from the work of Cockburn & Shu [1989a,1989b,1990,1998,2001]

**Recent Research:**

Attempts to reduce complexity and avoid quadrature:

- Spectral Difference (SD) scheme by Kopriva & Kolias [1996], Liu, Vinokur & Wang [2006]
- Nodal Discontinuous Galerkin (NDG) scheme by Atkins & Shu [1998], Hesthaven & Warburton [2007]
- Flux Reconstruction (FR) scheme by Huynh [2007,2009]

Cockburn, et al. (1989). J. Comput. Phys., 84(1); Cockburn, Shu (1989). Math. Comput., 52; Cockburn, et al. (1990). Math. Comput., 54(190); Cockburn, Shu (1998). J. Comput. Phys., 141; Cockburn, Shu (2001). J. Sci. Comput., 16; Kopriva, Kolias (1996). J. Comput. Phys., 125(1); Liu, et al. (2006). J. Comput. Phys., 216(2); Atkins, Shu (1998). AIAA J., 36(5); Hesthaven, Warburton, (Springer Verlag, 2007); Huynh, (2007). AIAA P., 2007-4079; Huynh, (2009) AIAA P., 2009-403

# DG, NDG, SD, FR

**Main Similarities Between Schemes:**

- Local discretization with element-wise polynomials
- Inter-element communication achieved through Riemann solver across interfaces

**Main Differences Between Schemes:**

- Discontinuous Galerkin: weak formulation requires the use of high-order quadrature rules to find flux discretization
- Nodal DG: discretizes flux in the same way solution is discretized: element-wise polynomials. Flux and solution points are coincident and located at the Gauss-Lobatto points
- Spectral Difference: uses differential formulation. Flux is discretized with element-wise polynomials one order higher than those used to discretize the solution. Solution and flux points are collocated.
- Flux Reconstruction: uses differential formulation. Flux and solution discretized with element-wise polynomials of the same order. Correction functions correct the flux and are polynomials of one order higher. Flux and solution points are coincident. Recovers previous schemes, hence facilitating analysis and comparison.

# Outline

I. The History of CFD

II. Author's Experience

III. Usage of CFD

IV. Current & Future Trends

V. Overview of Numerical Methods

**VI. Research on the FR Methodology**

- Energy stability
- Optimality of dispersion and dissipation properties
- Shock detection
- Filtering for non-linear stabilization

VII. Applications

VIII. LES Computations

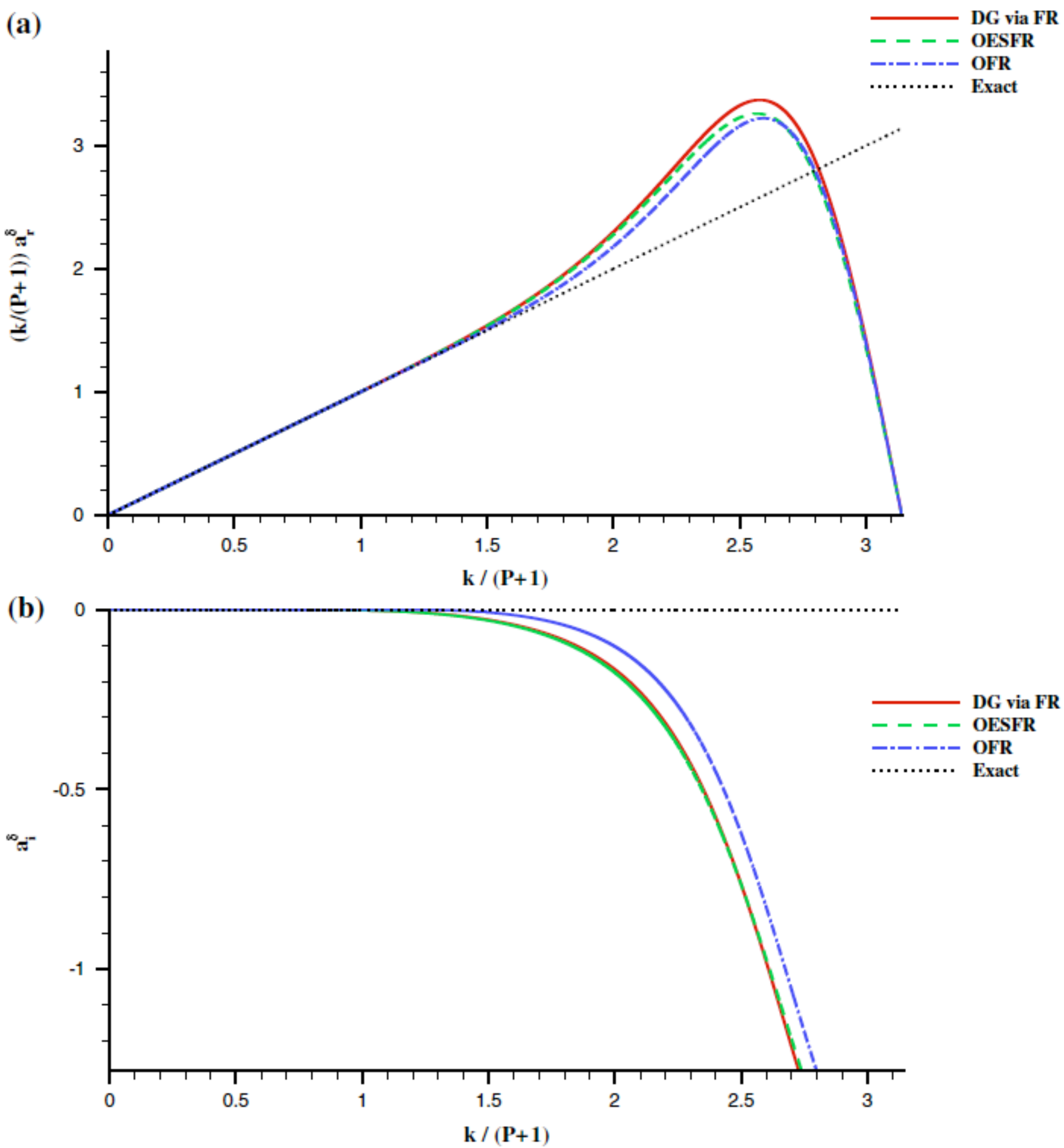
IX. Summary and Conclusions

# Linear Energy Stability

- **Energy stability analysis versus Fourier stability analysis**
  - Energy method is more general and rigorous
  - Energy method enables stability proofs for all orders of accuracy
  - Energy method applies to non-uniform meshes
  - *Fourier analysis provides more detailed information about the distribution of dispersive and diffusive errors*
  - *Fourier analysis identifies super accuracy for linear problems*

- **There exists a family of Flux Reconstruction schemes that are guaranteed to be linearly stable**
  - Parameterized with a constant $c$
  - Recover NDG, SD, plus other previously-found energy-stable FR schemes
  - $c$ changes the scheme, hence dispersion and dissipation properties too

# Optimal Flux Reconstruction (OFR)



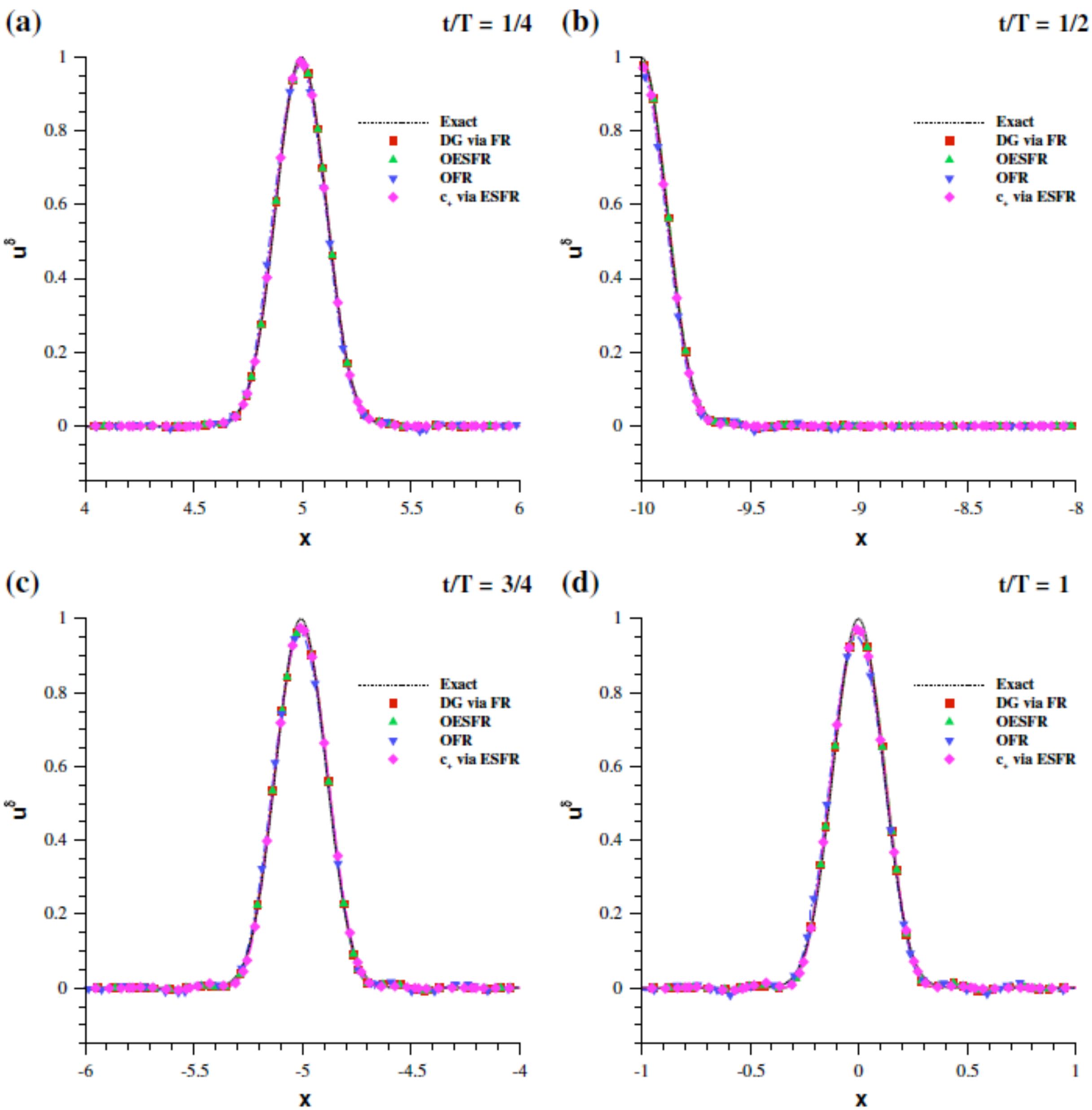

**Effective wavenumber**

**OESFR** - optimized by varying $c$
**OFR** - optimized by modifying zeros of correction function

**Imaginary part of numerical wavespeed**

Asthana et al. (2014). J. Comput. Phys.

# Optimal Flux Reconstruction (OFR)




**Advection of a Gaussian bump, P = 5**

- DG, OESFR: 61 elements
- OFR: 45 elements
- c+: 76 elements

**OESFR** - optimized by varying *c*

**OFR** - optimized by modifying zeros of correction function

Asthana et al. (2014). J. Comput. Phys.

# Shock Detection with the Concentration Method

Based on concentration method by Gelb, Gates, and Tadmore. Adapted to polynomials by Sheshadri.

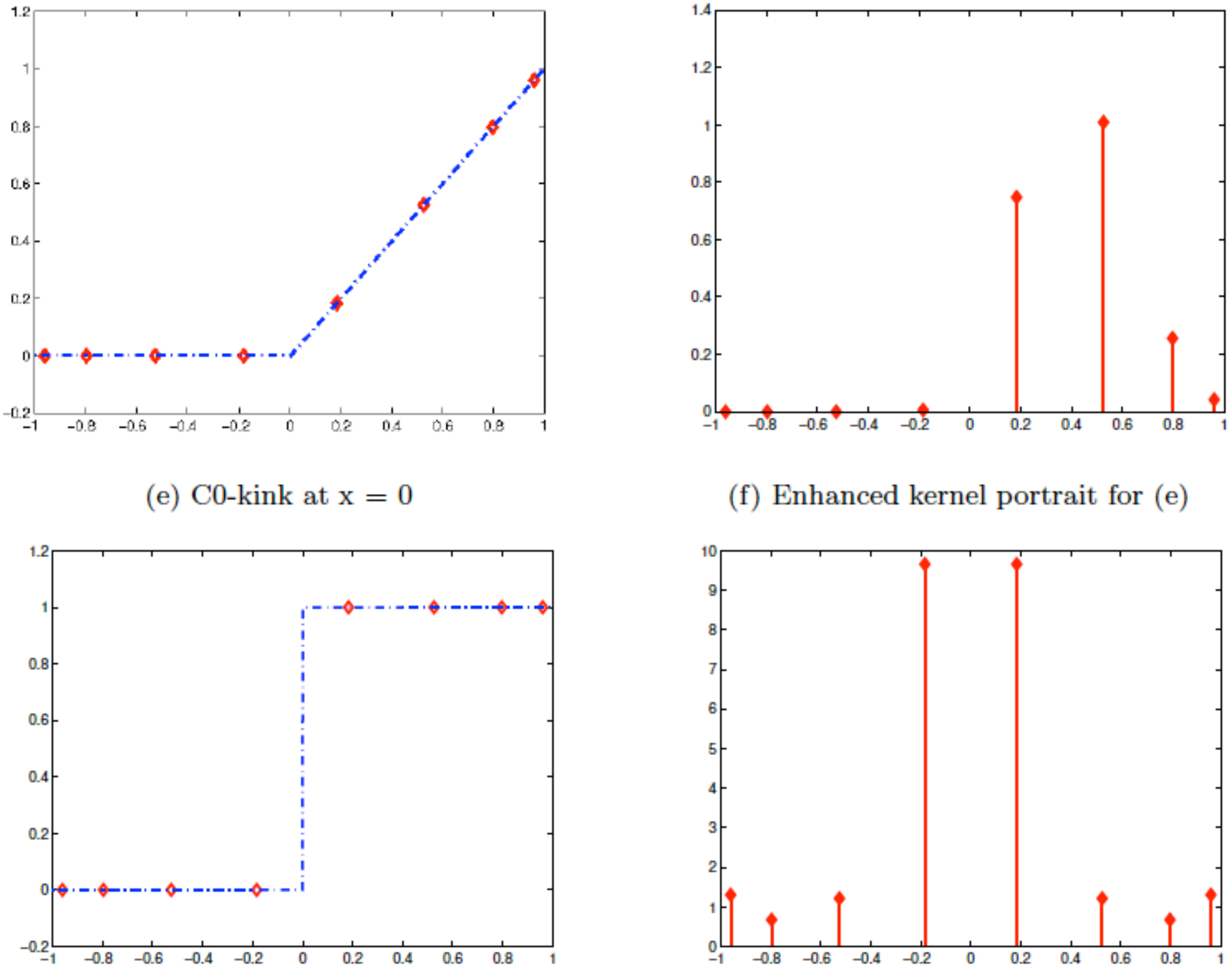
Steps:

**1.** Find polynomial modal decomposition (coefficients of Jacobi or Chebyshev bases)

**2.** "Enhance" decomposition via convolution with Kernel

**3.** If magnitude of coefficients is above a selected threshold, a discontinuity is present

Sheshadri, (2014) AIAA P., 2014-2688



(e) C0-kink at x = 0

(f) Enhanced kernel portrait for (e)

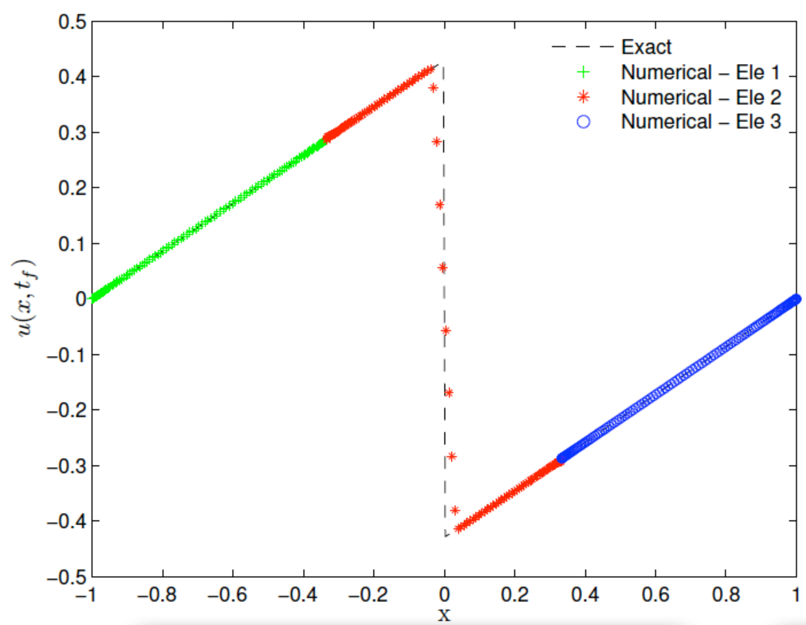
(a) Step at x = 0

(b) Enhanced kernel portrait for (a)

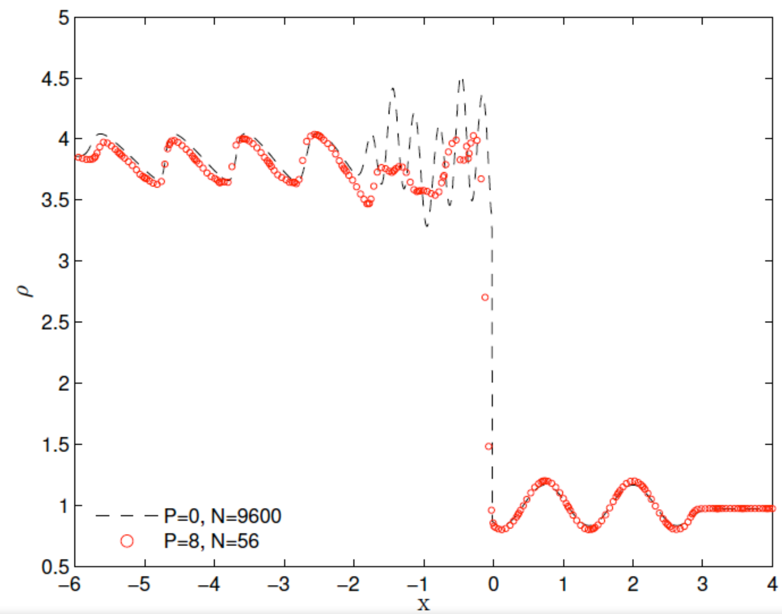
# Filtering for non-linear stabilization

Dissipation can stabilize FR schemes. Filtering can be posed as dissipation.

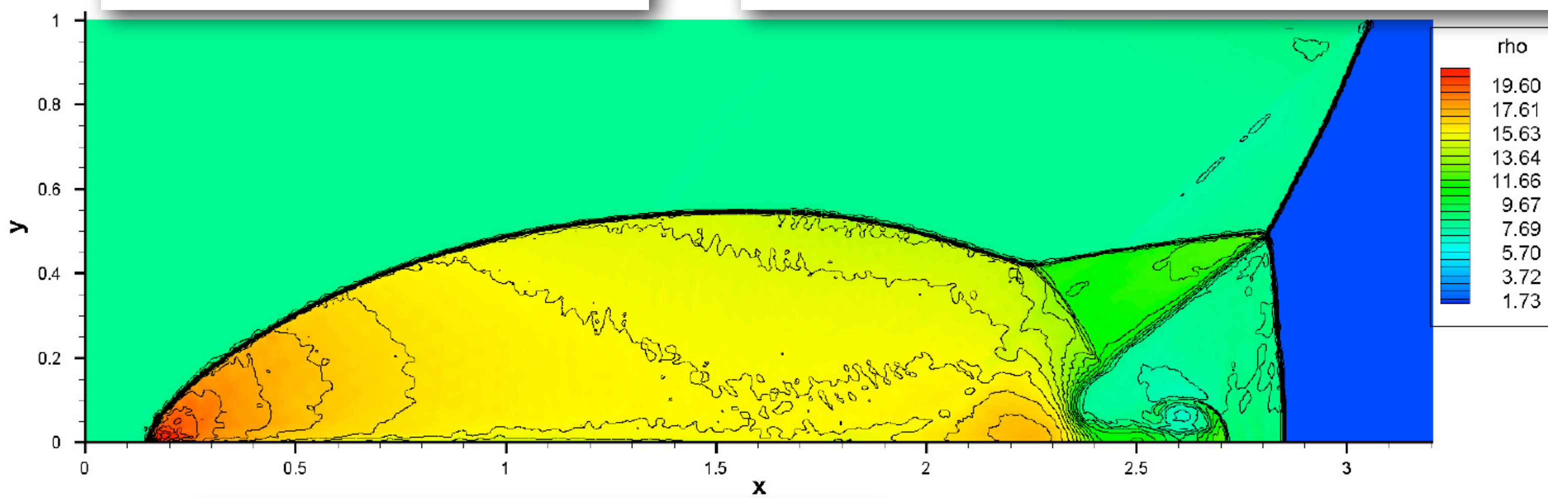
Local Fourier-Spectral (LFS) filters developed by Asthana et al. perform exact convolution locally and take neighboring information into account.




Burgers Equation, N = 3, P = 119




Shu-Osher shock-turbulence interaction, N = 56, P = 8




Double Mach reflection, N = 56x224, P = 8

**Asthana et al., (2014) submitted to JCP**

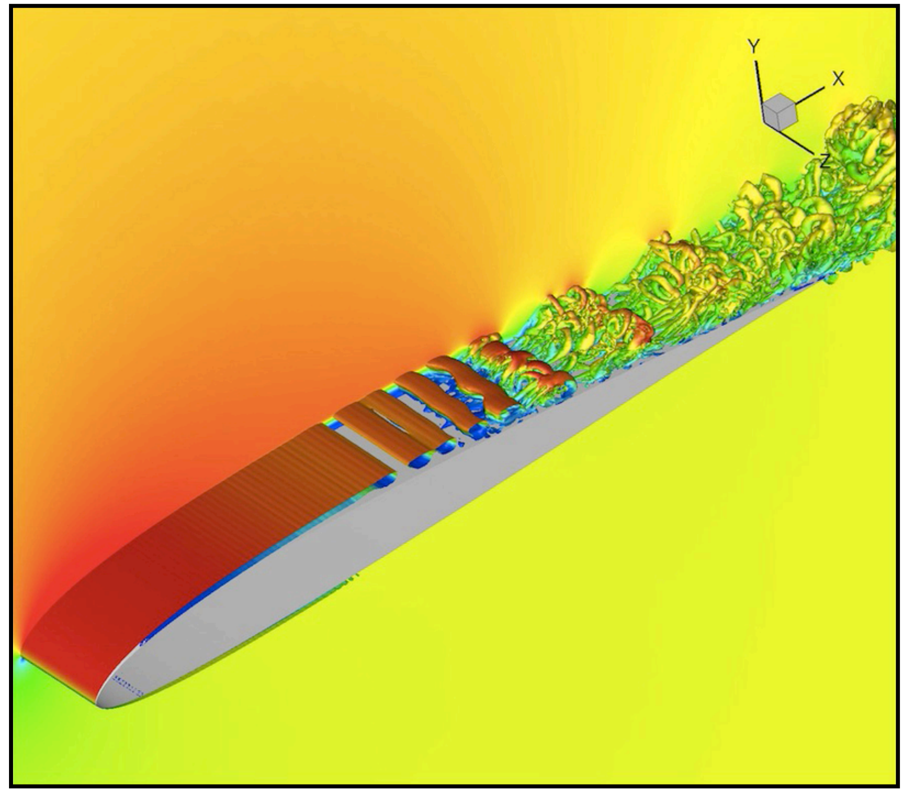
# Outline

# Transitional Flow over SD7003 Airfoil

| | Freestream Turbulence | Separation $x_{sep}/c$ | Transition $x_{tr}/c$ | Reattach. $x_r/c$ |
|---|---|---|---|---|
| Radespiel et al. | 0.08% | 0.30 | 0.53 | 0.64 |
| Ol et al. | 0.10% | 0.18 | 0.47 | 0.58 |
| Galbraith Visbal | 0% | 0.23 | 0.55 | 0.65 |
| Uranga et al. | 0% | 0.23 | 0.51 | 0.60 |
| Present ILES* | **0%** | **0.23** | **0.53** | **0.64** |

Experiments in green

**SD scheme, N=4**



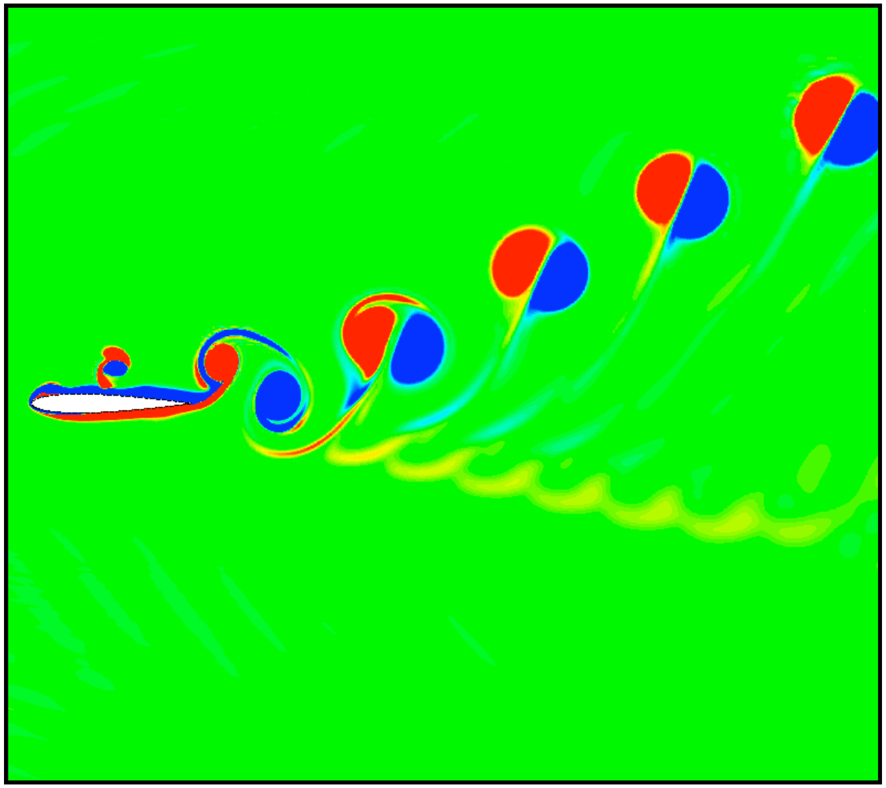

Iso-$Q$ colored by Ma

**Re=$6\times10^4$, AoA=$4^\circ$, $2.2\times10^7$ DoF**

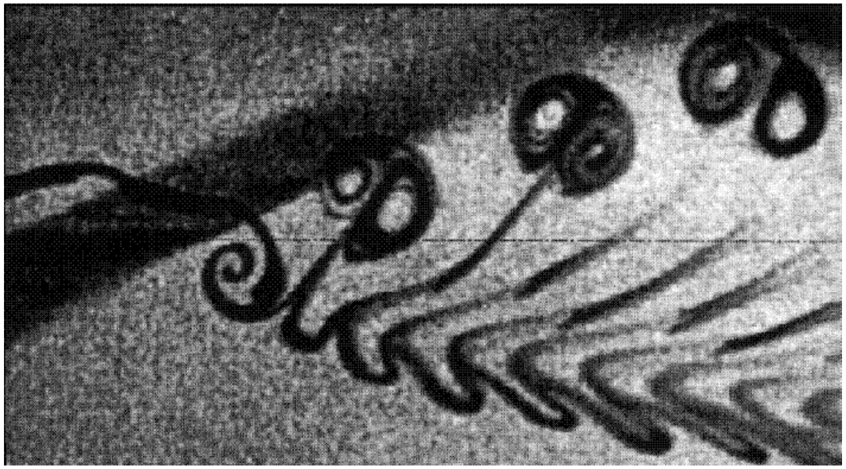
***$1.7\times10^6$ DoF**

**Castonguay, et al. (2010). AIAA P., 2010-4626; Radespiel, et al. (2007). AIAA J., 45(6); Ol, et al. (2005). AIAA P., 2005-5149; Galbraith, Visbal (2008). AIAA P., 2008-225; Uranga, et al. (2009). AIAA P., 2009-4131;**

# Study of Flapping Wing Sections



SD, 2D, N=5 on deforming grid

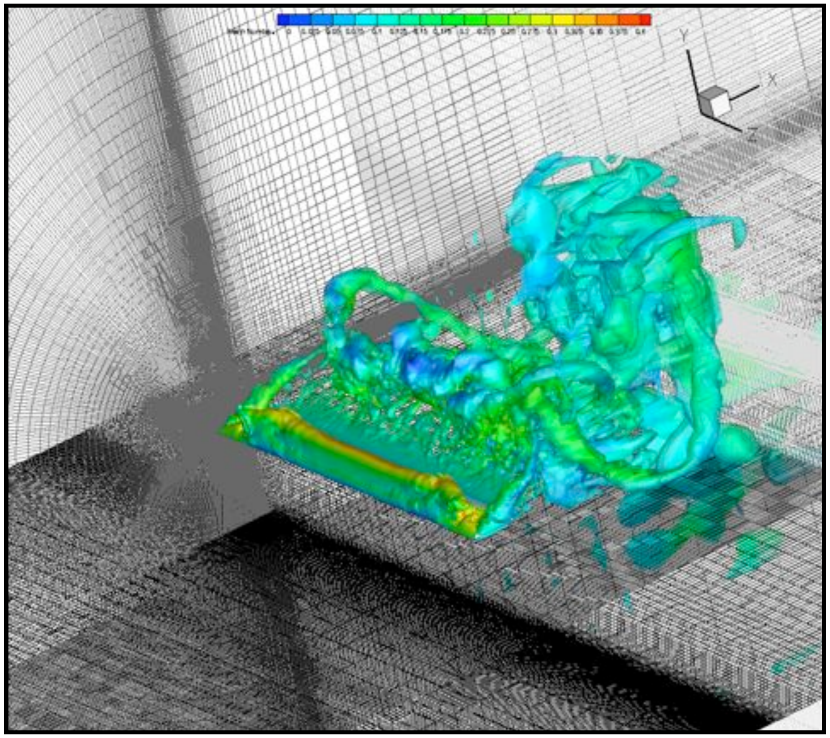


Experiment (Jones, et al.)

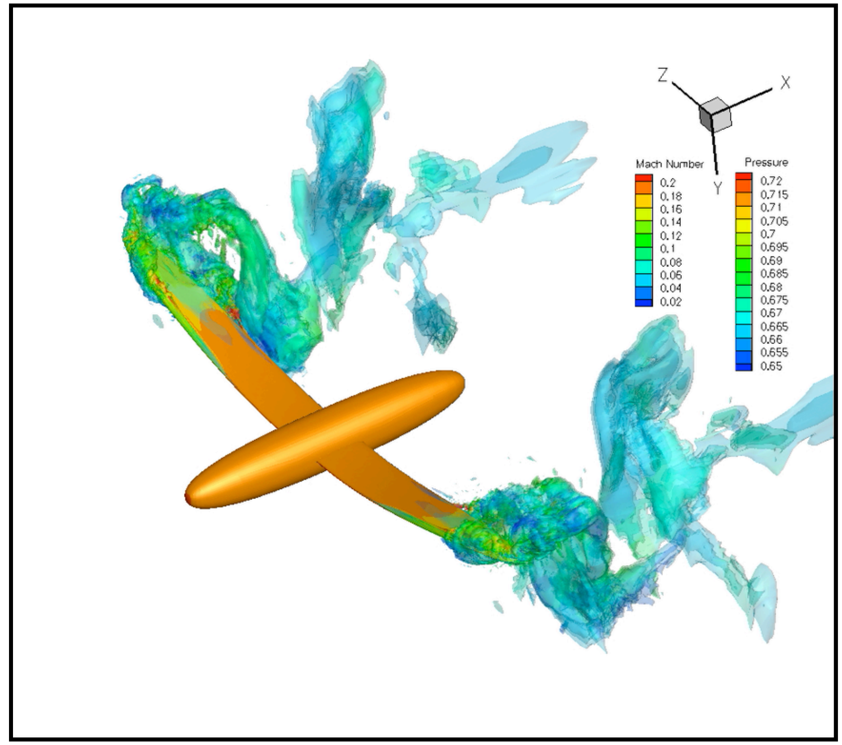
**NACA0012, Re=1850, Ma=0.2, St=1.5, $\omega$=2.46, $h$=0.12$c$**

Jones, et al. (1998). AIAA J., 36(7)

# Flapping Wing Aerodynamics



Iso-Entropy colored by Ma



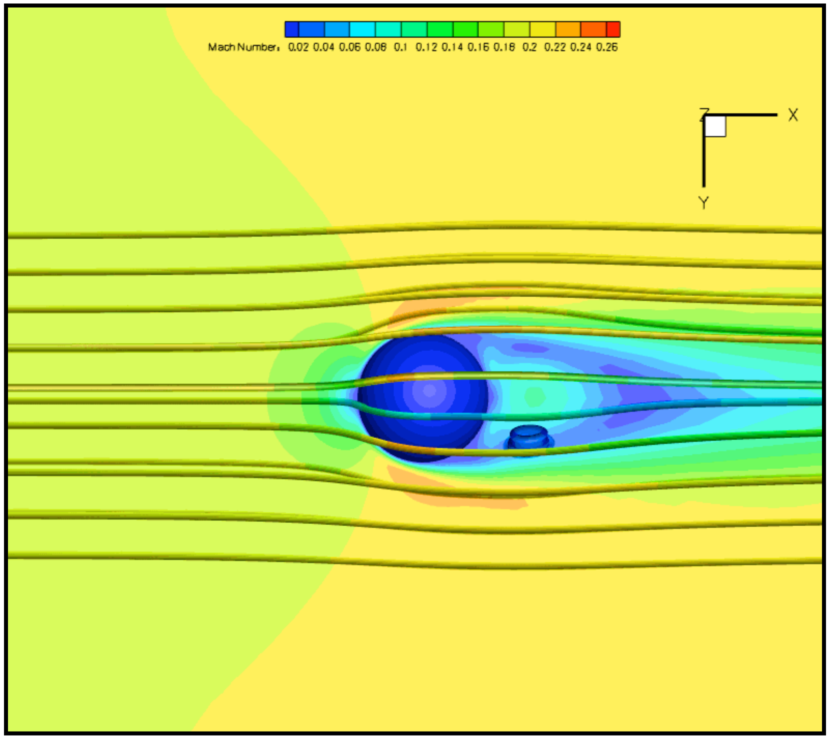

Iso-Entropy colored by Ma

**Flapping NACA0012, Re=2000,**
**SD N=5, $4.7\times10^6$ DoF**

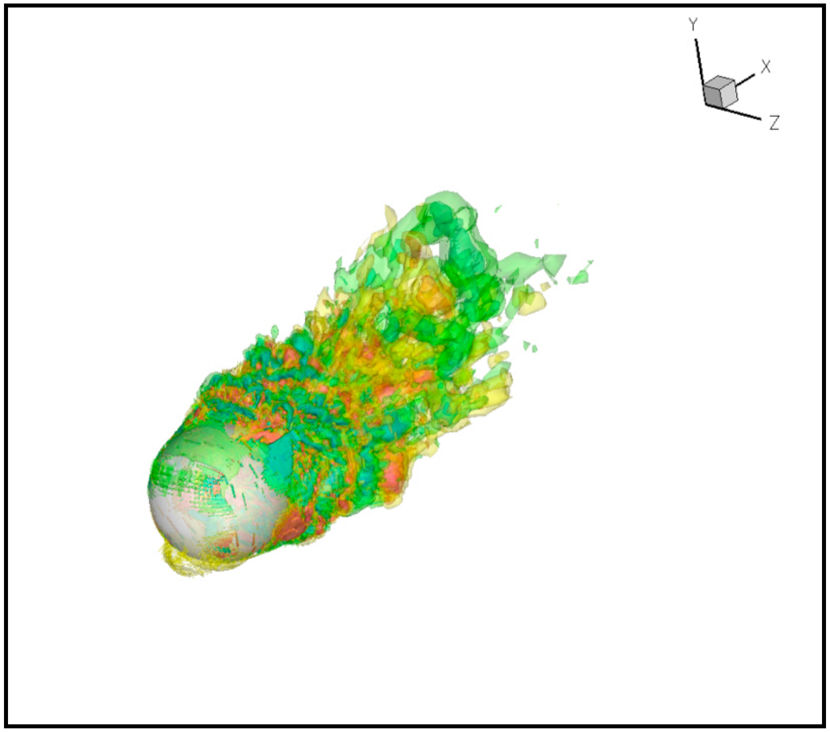
**Wing-Body, Re=5000,**
**SD N=4, $2.1\times10^7$ DoF**

Ou, et al. (2011). AIAA P., 2011-1316; Ou, Jameson (2011). AIAA P., 2011-3068

# Flow Over Spheres




Mach contours + streamlines




Iso-Vorticity colored by Mach

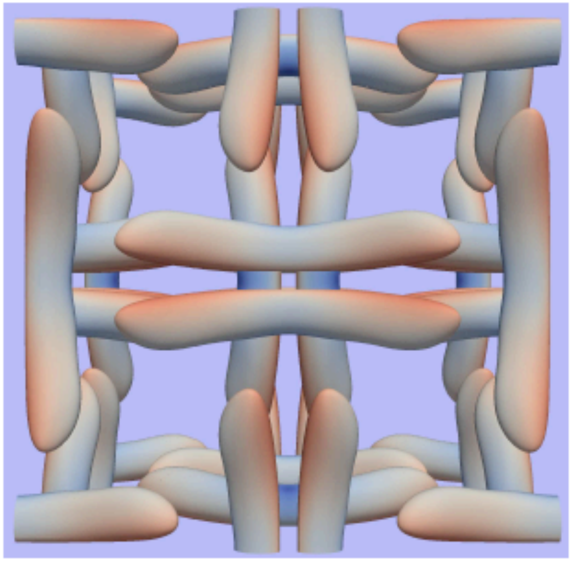
**Flow over a spinning sphere,**
**Re=300, Ma=0.2**

**Flow over a sphere,**
**Re=10000, Ma=0.2**

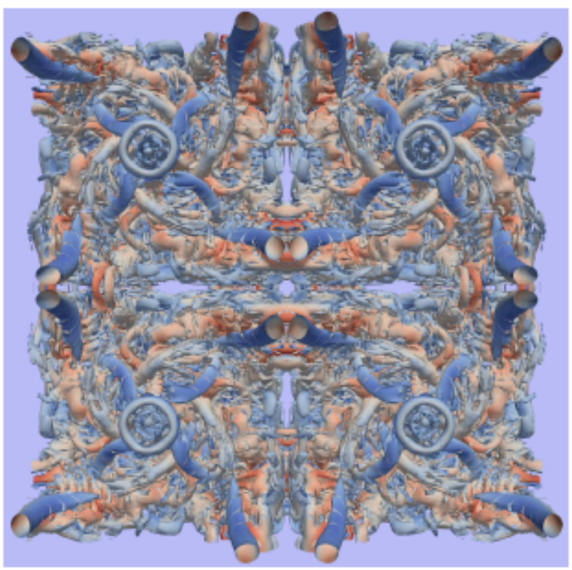
Ou, et al. (2011). AIAA P., 2011-3668

# Outline

# Taylor Green Vortex: $Re_D = 21400$

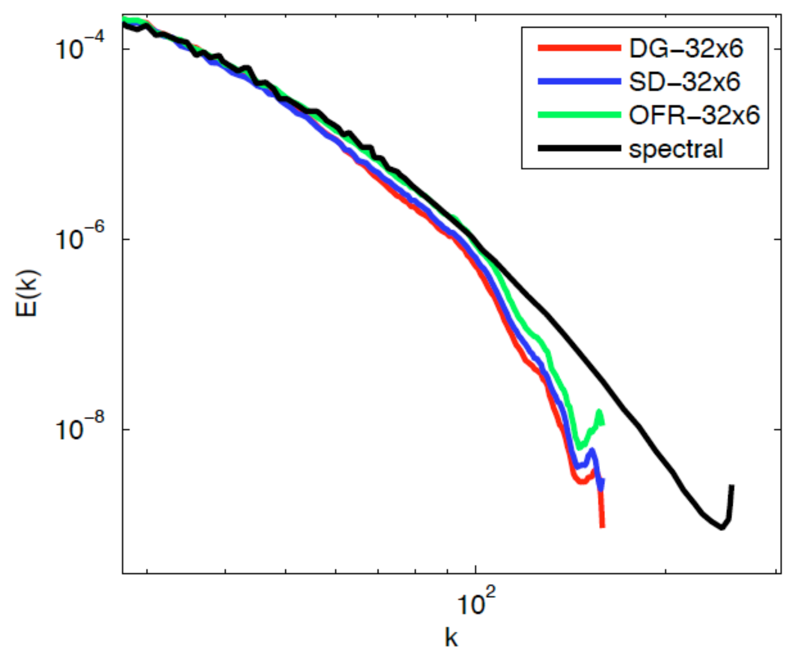


(a) $t = 2.5$, $Q = 0.5$



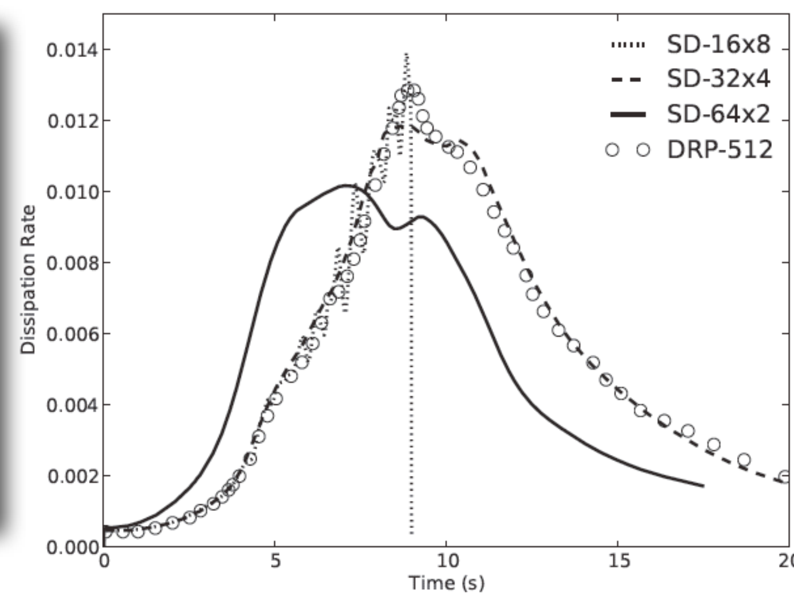
(d) $t = 10.75$, $Q = 1.5$

Iso-$Q$ colored by velocity magnitude

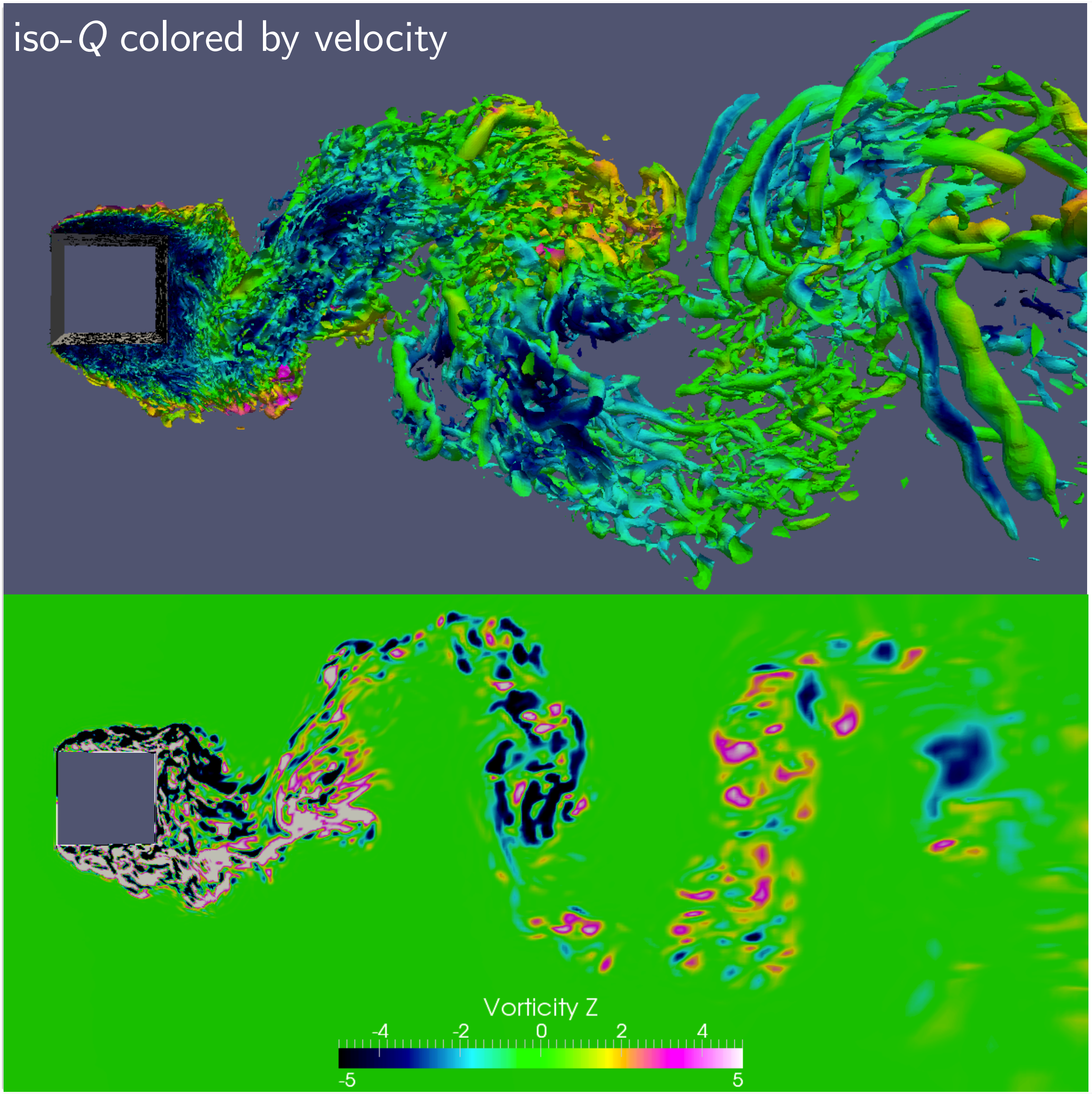


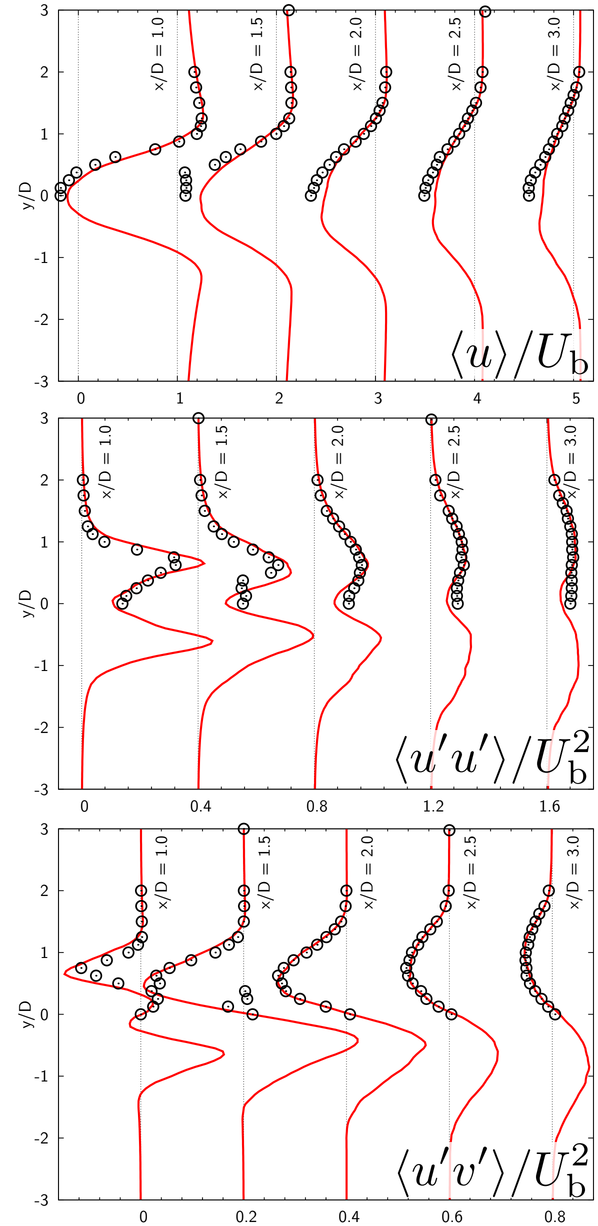

Energy spectra for different FR-derived schemes, compared to a spectral method on a $512^3$ grid, at $t = 9$ *sec*

Dissipation rate over time of FR-derived SD scheme compared to a 13-point Dispersion-Relation-Preserving (DRP) Finite Difference scheme on a $512^3$ grid. The number of degrees of freedom remain constant in the different schemes. 8th order scheme becomes unstable because of aliasing.



# Flow past a Square Cylinder: $Re_D = 21400$



# Outline

# Summary and Conclusions

**Predicting the future is generally ill advised.**
**However, the following are the author's opinions:**

- The early development of CFD in the Aerospace Industry was primarily driven by the need to calculate steady transonic flows: ***this problem is quite well solved***
- CFD has been on a plateau for the last 15 years with 2nd-order accurate FV methods for the RANS equations almost universally used in both commercial and government codes which can treat complex configurations. These methods cannot reliably predict complex separated, unsteady and vortex dominated flows
- Ongoing advances in both numerical algorithms and computer hardware and software should enable an advance to LES for industrial applications within the foreseeable future
- Research should focus on high-order methods with minimal numerical dissipation for unstructured meshes to enable the treatment of complex configurations

# Summary and Conclusions

**Current obstacles to the wider adoption of high-order methods which call for further research include:**

- slow convergence for steady state problems - this might be alleviated by a better design of a multi-hp convergence acceleration scheme
- the need for a more efficient implicit time stepping scheme for unsteady problems
- more robust high-order schemes for nonlinear problems such as are encountered in high speed gas dynamics
- more efficient and user friendly mesh generation techniques

# Summary and Conclusions

**Current issues in LES include:**

- the need for wall models to enable simulations of wall bounded flows at affordable computational costs
- the need for further research on subgrid filtering techniques on unstructured meshes
- the need for continuing research on subgrid models, including approximate deconvolution and exact SGS models, and a careful evaluation of implicit LES methods

**Automatic shape design methods based on control theory or other optimization methods will be increasingly used in aerospace design**

**Design problems in unsteady flow, such as turbomachinery, rotorcraft, or unsteady separated flows are particularly challenging**

# Summary and Conclusions

Eventually DNS may become feasible for high Reynolds number flows

hopefully with a smaller power requirement than a wind tunnel

# Acknowledgement

**The current research is a combined effort by**

- *Postdocs*: Jonathan Bull, Guido Lodato
- *Ph.D. students*: Manuel López, Kartikey Asthana, Abhishek Sheshadri, Jacob Cabrill, Joshua Romero, Jerry Watkins, David Manosalvas

**It is made possible by the support of**

- the *Air Force Office of Scientific Research* under grants FA9550-10-1-0418 and FA9550-14-1-0186 monitored by Dr. Fariba Fahroo
- the *National Science Foundation* under grants 0708071 and 0915006 monitored by Dr. Leland Jameson
- Stanford Graduate Fellowship

# Questions & Anwers

**Thank you for listening**